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EVALUATION OF SOUND QUALITY FEATURES ON ENVIRONMENTAL NOISE EFFECTS – A CASE STUDY APPLIED TO ROAD TRAFFIC NOISE

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Abstract

The paper shows a study on the relationship between noise measures and *sound quality* (SQ) features that are related to annoyance caused by the traffic noise. First, a methodology to perform analyses related to the traffic noise annoyance is described including references to parameters of the assessment of road noise sources. Next, the measurement setup, location and results are presented along with the derived sound quality features. Then, statistical analyses are performed to compare the measurement results and sound quality features. The included conclusions are focused on showing that the obtained loudness values, regardless of the used system, are similar in a statistical sense. Contrarily, sharpness, roughness and fluctuation strength values differ for the tools employed.

Keywords: sound quality, annoyance, traffic noise.

1. Introduction

The aim of this paper is to obtain information on the assessment of the noise annoyance perception in a residential area, derived from the flow of vehicles treated as moving noise sources. A novel approach is introduced, which does not involve the commonly used methodology, but is based on the analysis of correlation between the parameter values obtained from measurements and the *sound quality* (SQ) features, *i.e.*: loudness, roughness, sharpness and fluctuation strength – to derive conclusions on noise annoyance.

The noise sources of an urbanized environment cause the sound pollution, but can also result in negative effects experienced by people. Depending on the type of source, its intensity and frequency, an assessment of the impact of noise sources can be quantitative and qualitative. The regulations of the EU Directive [1] refer to the assessment and management of environmental noise caused by traffic, industry and recreation in the open air. By definition noise in the environment is unwanted or harmful outdoor noise created by the human activities, including

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the traffic noise. According to art. 7 of the Directive [1], the requirements for the preparation of strategic noise maps have been specified as part of the noise assessment and management.

Depending on the type of road noise sources and their traffic parameters, we are dealing with a diverse impact on recipients. The impact depends on many variables concerned with the relationship: noise source – propagation path – receiver. With regard to the duration of acoustic signals, this relationship depends not only on the psychophysical characteristics of the noise sources, but it is associated with the environment characteristics such as: the distance between the source and the receiver, the density of buildings, the acoustic properties of reflecting and absorbing surfaces. For modelling the traffic noise, the data of selected elements of digital maps, which are related to sources, infrastructure, buildings, and other map features potentially influencing the environmental noise are used [2].

Due to the diversity of noise sources and the areas in which they are present, various relevant indicators of noise hazard assessment have been introduced, *i.e.*: short-term indicators of equivalent sound: L_{AeqD}, L_{AeqN} and day-evening-night long-term indicators of noise level L_{DWN}, as well as indicators of noise level at night time L_N [1, 3, 4].

An example of a distributed noise monitoring system based on a wireless acoustic sensor network is shown in the work of Garcia *et al.* [5]. This methodology is applied to the study of the spatial evolution in time of the noise pollution. Such an approach requires a selection of technical, legal and organizational solutions, that minimize acoustic hazards in the analysed areas [6]. To determine the global assessment of noise indicators in an area to be analysed, it may be necessary to acquire also the demographic data – population density, data on the location of health and educational facilities, which should be protected against noise, such as schools, hospitals *etc*. [7–10].

Acoustic maps are characterized by uncertainty, which is usually related to the accuracy of mapping of the studied area and the quality of acoustic calculations. Uncertainty may also result from the acquisition of incorrect input data, an incorrect calculation method, errors in numerical calculations or validation/verification of computational models. Based on generated calculation results, the information on possible dispersion of estimated levels of the noise hazard is obtained, what proves to be significant in the tasks of the environmental protection programs and in estimation of investment costs. In particular, the accuracy and timeliness of acoustic maps also depend on non-acoustic data. These include parameters characterizing density of road, rail and air traffic, which can be determined simultaneously with the acoustic measurements or obtained from the external resources [10–12]. Uncertainty of acoustic maps is additionally emphasized by the aspects of establishing the uniform time, or ensuring the stability of meteorological conditions during acoustic measurements [10]. Finally, another aspect of uncertainty in the road traffic noise modelling is related to the technical conditions of the pavement, the density of traffic and the average speed of traffic flow. In addition, some of such data are usually evaluated subjectively [9]. Moreover, the use of *information technology* (IT) in the noise pollution assessment is visible [13, 14]. This is especially important with regard to the impact of temporal aspects of environmental noise of cities. To show variability of noise sources intensity, in selected periods of a year, week or day several aspects should be taken into account. For example:

– some sections of the road can be more frequented during weekends;
– noise maps do not include the maximum daily/hourly values of sound level, which may be diverse;
– models of noise sources do not include specific acoustic effects, such as sounds of brakes, sounds of emergency vehicles, honking sounds etc.

Modelling of acoustic phenomena for the forecasting of environmental noise consists, among others, in determining the relationship between the features characterizing the sound field, and the parameters characterizing the sound source and propagation conditions. On the other hand, in the noise hazard assessment, the relationship between the type of terrain and the quantitative indicators of noise assessment are to be taken into consideration. In addition, the Directive [1], specifying the guidelines for the development of acoustic maps, refers to the assessment of the impact of harmful results of noise. Accordingly, in assessing the effects of noise on populations, there should be applied the noise dose-consequence relationship. Although there are currently no developed standards for the noise dose-effect factors, in the future they are planned to be based on the relationship between annoyance and L_{den}, L_{night} for, among others, the vehicular traffic noise. According to [1], the annoyance is defined as the degree of discomfort for the community, which was established on the basis of research results in the field. Unfortunately, in this document, there is no recommendation on a model of its representation, as well as a way of obtaining it.

The results of the research conducted by Kaczmarek and Preis on the perception of sound phenomena in the environment indicate the importance of sound quality features that express subjective impressions of the received acoustic signals [15]. The methods used to assess the noise annoyance of moving sound sources, derived from objective and psychoacoustic annoyance formulae, do not take into account the time variability of all sound quality features [16]. It is assumed in these formulae that loudness is the primary noise annoyance factor. What is also taken into consideration is the importance of the duration of the sound event of a source above the background noise [15]. The methods used are some approximation of the annoyance assessment, conditioned by the accepted assumptions and simplifications, that rely on modelling the psychoacoustic assessment of sound quality. The authors of this paper showed however a limited use of these models because they do not always confirm the test results obtained in laboratory conditions. These results indicate, among others, the diversity of values received within the ICBEN (*International Commission on Biological Effects of Noise*) scale, in relation to the psychoacoustic annoyance, due to shaping sound sharpness [15].

The annoyance caused by the road noise is also reported in other research studies in the literature [17, 18]. They show that the type of noise annoyance scale and the aspects of its presentation and other contextual factors may affect the self-reported noise annoyance. This means that the subjective aspect of the noise road annoyance is very important. Méline *et al.* found that the resulting annoyance may depend on individual/neighbourhood socio-demographic factors [18]. Based on their study, they suggest that it is useful to take into account not only the exposure to the transportation noise in a residential neighbourhood but also at a residence, as well as the socioeconomic characteristics of a residential neighbourhood to explain variations in the subjectively perceived annoyance due to the road traffic in the neighbourhood. A recent work by one of the authors and his collaborators studied the problem of noise modelling of industrial and communication sources using data-mining algorithms, which help while dealing with many factors underlying noise assessment [19–21].

This paper is organized as follows: Section 2 describes the proposed methodology , focusing on the road noise source assessment measures, taking into account the road surface. Then, the measurement setup, location and measurement results are presented in Section 3. In Section 4 the parameters and SQ features derived from the measurements by a Pulse Reflex meter are compared with those obtained with the LabView. This Section includes also statistical analyses performed on the basis of the obtained results. Finally, the conclusions derived from this study are shown.

2. Methodology

The issues undertaken in the paper involve trying to find the relationship between the psychophysical sound assessment and the evaluation of impressions of sound perception, in multi-family housing areas.

The research undertaken by the authors is aimed at assessing the psychophysical features of sound for the purpose of estimating the sound perception. It is part of a larger research framework investigating the usability of SQ features and annoyance, and it involves several stages. The paper concerns the first phase of this framework, which includes the analysis and assessment of psychophysical features of sound in selected areas of the environment being at risk of noise pollution. The next phase of research is to be directed at the assessment of perception of recorded signals. Therefore, the aim of the recordings was to collect the real audio material reflecting the auditory sensations, which a person on a sidewalk in an immediate vicinity of a busy road is exposed to. The material is supposed to be used in the future for subjective assessment of the nuisance of road noise using the method of loudness scaling.

As already mentioned, the essence of this study does not concern estimating the effects of noise annoyance, according to the commonly used methodology, but it involves obtaining information on the assessment of the noise perception in a residential area, extracted from the flow of vehicles. The problem of acoustic comfort assessment is important because of the universality of the harmfulness of noise to the population, caused by the impact of the movement of vehicles in long periods of time. It is assumed that in the study of psychophysical assessment of sound, the following features will be considered:

– physical: L_{Aeq}, L_{AFmin}, L_{AFmax}, L_{Cpkmax};
– sound quality: loudness, roughness, sharpness and fluctuation.

As a starting point for acoustic measurements, reference points in a urbanized environment impacted by the road traffic noise should be chosen. The same measurement procedure should be applied independently of acoustic event types and locations according to the guidelines of the Ministry of the Environment [22]. It was established that for the purpose of determining the physical sound parameters and sound quality features the acoustic signals need to be recorded. The duration of the recording was set to 5 minutes. The measurements were oriented towards the harmful effects of noise; that is why they were made as explained in Subsection 3.3, *i.e.* at the head height of a potential passer-by and halfway up the width of the sidewalk. In the performed analysis there were determined the sound quality assessment features and their correlation, as presented further.

Because of the specifics of varying noise sources, the issue becomes further complicated, due to the occurrence of variations in energy in time. Considering the volatility of this energy, this becomes an additional problem in modelling the assessment of noise annoyance.

In this study variability of the acoustic density of vehicle traffic, which depends not only on the stream and the type structure of the vehicles, but also on the type and condition of the road surface are to be taken into account. The noise level depends not only on the acoustic power of a source itself but also on the relation of the factors related to the locations of the source and the receiver. To generalize, regardless of the type of vehicle or group of vehicles the impact of noise sources' emission on people is undesirable and in consequence may be annoying [17].

Individual evaluation of the impact of noise sources in connection with the specificity of the context of its perception makes it difficult to perform a representative noise annoyance assessment. In addition, the problem of changes of the location of a source over time is imposed on these conditions [18]. Loudness, as a primary measure of sound quality, exhibits non-linearity of the sound level as a function of frequency and sound level. Shaping up loudness for time-varying sounds varies in relation to the sound level and depends on the duration of sound [23]. In the used models of the loudness assessment, percentile measures N_5, N_{10} in relation to the duration of sound were proposed [16, 24]. However, using either of these two models, brought no satisfactory estimation of loudness.

As already mentioned, the basic psychoacoustic measure of the annoyance assessment of time-varying sounds is loudness, which is a standardized measure according to [25]. While loudness of stationary sounds has been standardized for decades, the standards for sharpness of stationary sounds [26] and for loudness of time-varying sounds [25] were published in 2009 and 2010. The standard for roughness of time-variant sounds was presented in 2013 [27] and a new ISO standard for loudness – in 2017 [28].

Moreover, the non-linear nature of loudness, corresponding to the time-varying sounds, makes it difficult to determine the resultant loudness. In accordance with the standard [25], the time-varying loudness is determined by analysis of 1/3 octave spectrum, using the exponential average, with a time constant of 2 ms. The calculations are carried out in the critical bands, taking into account the phenomenon of masking. Additional features, *i.e.* sharpness and tonality are standardized only for stationary signals. Other features, *i.e.* roughness and fluctuation strength are determined based on the adopted procedures, but they are not standardized features. The roughness is the ear impression associated with the speed of amplitude modulation (15–300 Hz). Works on the development of the roughness standardization are in progress. The fluctuation strength is associated with the amplitude depth and is perceived when the modulation frequency is below 20 Hz. The perception of sounds depending on the time structure, amplitude or frequency changes may also vary with unchanged (constant) loudness.

For the purpose of analysing the sound quality features of recorded traffic noise samples (containing road characteristics), specialized signal processing tools: LabView and Pulse Reflex were used. According to the documentation provided by the LabView system [29] the sound quality features are determined by the following procedures:

- time-varying loudness – according to [25]. This algorithm measures the 1/3 octave spectrum using exponential averaging with a 2 ms time constant, combines the fractional-octave bands into critical bands, and applies temporal and spectral masking;
- roughness – the roughness algorithm measures energy in 24 Barks, computes and filters the envelope of the signal in each band, measures the amplitude modulation of each envelope, and then weights the level in each band using both the modulation index of that band and a frequency-dependent weighting function;
- sharpness – the sharpness algorithm computes sharpness from the sound pressure signal waveform, the 1/3-octave band spectrum calculated over the frequency range 25 Hz to 12.5 kHz, or the specific loudness. This algorithm normalizes the specific loudness spectrum by the total loudness and weights the spectrum according to frequency;
- fluctuation strength – is measured in terms of energy in 47 overlapping Bark bands, computes and filters the envelope of the signal in each band, measures the amplitude modulation of each envelope, and weights the level in each band using a frequency-dependent weighting function. The algorithm examines modulations between 0 to 30 Hz, with a special emphasis on those near 4 Hz.

The SQ features calculated by the Pulse Reflex system are given further on in Section 4.

It is assumed that the obtained results of sound quality features along with the evaluation of traffic noise perception in laboratory conditions are to be used to construct a model of the noise nuisance caused by the impact of moving sound sources.

3. Measurements

The aim of the measurements was two-fold, first of all it was to collect the audio data for analysis of the noise indicators, and secondly – as already mentioned – to gather the sound material reflecting the noise annoyance. The latter goal is to be fulfilled in the future study of subjective assessment of the nuisance of traffic noise using the method of loudness scaling. It is worth emphasizing that the measurement results are not employed to assess noise in assigned locations in accordance with the reference conditions [3]; they will only be used – in the future study of subjective listening – to replicate in laboratory conditions the acoustic situations occurring in an immediate vicinity of the road. This is to ensure that the same acoustic energy of the audio material is obtained while playing it from a loudspeaker in free-field conditions. Therefore, it was an intentional decision taken by the authors not to set a microphone in accordance with the reference conditions, as the primary objective was to obtain the most realistic audio recordings to be assessed by listeners evaluating the noise annoyance.

3.1. Measurement setup

The following set of equipment was used for recording and measurements:
- a sound Level Meter Brüel & Kjær 2238 Mediator;
- Brüel & Kjær Free-Field Microphone 4188;
- Zoom Handy Sound Recorder H4n;
- a microphone stand;
- Brüel & Kjær Calibrator type 4231.

Prior to the recordings and measurements, the whole setup was calibrated. The recordings and measurements were made simultaneously. The microphone with the meter was put on the stand and placed along the traffic lane. The audio signals were recorded on the separate recorder in a lossless WAV format. The signal source for the recorder was the line output of the sound level meter. In this way, a signal coming from the measurement microphone was used in parallel for both the measurement and the recording. The recording and measurement periods were set to 5 minutes. The recorded material was then used to select 10 short sound samples for which the SQ parameters were to be calculated. The acoustic parameters of sound measured during the recording of audio material would only be used to replicate an acoustic situation in laboratory conditions and would not be used to assess the noise annoyance in this environment.

3.2. Measurement location

The acoustic measurements and recordings were made in Gliwice during a weekday, between 11.00 a.m. and 1.00 p.m. Two locations, where residents particularly complained about the nuisance of street traffic, were selected for the measurement. The characteristics of measurement and recording locations (A) and (B) are described below:

(A) 13a Dolnych Wałów Street
- pavement (road surface): cobblestone, two-way, single carriageway, road width: 8.7 m, sidewalk width: 2 m;
- the distance from the sidewalk to the first building line: 0;

(B) 10a Kozielska Street
- pavement (road surface): tarmac, two-way, single carriageway, road width: 8.4 m, sidewalk width: 4.1 m;
- the distance from the sidewalk to the first building line: 0.

These locations were selected intentionally, mainly for the type of pavement as well as the traffic density. The traffic of passenger cars was characterized by similar values of intensity and speed (about 40 km/h) in the points examined. In particular, the road surface in the (A) measurement point was made of sharp-edged cobblestones, whereas in the (B) measurement point – of tarmac. During measurements the road surfaces were dry and meteorological conditions were satisfactory. In addition, these points have features that differentiate them from other locations. There are two- and three-storey buildings in the immediate vicinity of the roads, which constitutes specific duct- or canyon-like configurations of both locations.

3.3. Measurements and results

The aim of the recordings was to collect the real research material reflecting the auditory sensations which a person on a sidewalk in an immediate vicinity of a busy road was exposed to. The material was supposed to be used in the future for the subjective assessment of the nuisance of traffic noise using the method of loudness scaling [15, 30]. During the recordings and measurements, the microphone was placed on the stand at a height of 170 cm, which is a head height of a potential adult passer-by, and halfway up the width of the sidewalk, *i.e.* in a place where the pedestrian traffic is normally the heaviest. The recordings and measurements were one-off, with no repetition. It is worth emphasizing that the obtained measurement results will not be used to assess noise in the assigned locations in accordance with the reference conditions [22]; they will only be used to replicate in laboratory conditions the acoustic situations occurring in an immediate vicinity of the road.

The parameters measured during a recording session were as follows:

– equivalent sound pressure level (L_{Aeq}) corrected by curve *A* (equivalent continuous level for a measurement as defined by IEC61672, freq. weighting *A*);
– minimum sound pressure level (L_{AFmin}) corrected by curve *A* averaged exponentially with a time constant F (min value detected within the elapsed time, freq. weighting *A*);
– maximum sound pressure level (L_{AFmax}) corrected by curve *A* averaged exponentially with a time constant F (max value detected within the elapsed time, freq. weighting *A*);
– peak sound pressure level (L_{Cpkmax}) corrected by curve *C* (max peak level detected within the elapsed time, freq. weighting *C*);
– reference pressure: 20 μPa.

In this way, two (location-based) five-minute sound files were prepared. The values of acoustic parameters derived from the measurements are shown in Table 1.

Table 1. The values of acoustic parameters of five-minute sound files and the numbers of vehicles passing the locations during the measurements.

LOCATION	NUMBER OF CARS	L_{Aeq} [dB]	$L_{AF\,min}$ [dB]	$L_{AF\,max}$ [dB]	$L_{Cpk\,max}$ [dB]
A	33	72.7	53.1	86.1	103.5
B	45	70.4	49.9	81.8	98.8

The L_{Aeq} level as well as other maximum values obtained in location (B) – tarmac pavement are lower than those in location (A), although the traffic in (B) was heavier than in (A). The lowest level of 49.9 dB was recorded also in location (B), and it was a situation with no car traffic in the street while performing the measurement.

The obtained sound files constitute the basis for future subjective tests that will be used to evaluate the sound quality measures and to determine the traffic noise annoyance in laboratory conditions. This assessment will involve persons with normal hearing as well as hearing-impaired ones. Due to the fact that some elderly persons will also be part of the assessment team, it has been decided to select short samples so that they are not tiresome for them. For this reason, only ten 10-second excerpts were selected from each (location-based) 5-minute file. The length of sample was defined in this way because the whole acoustic event stays within this time limit, *i.e.* from the moment a vehicle arrives, till it departs.

As previously mentioned, the lowest level of the background noise (ambient noise) in the locations was 49.9 dB. After analysing the audio material, it turned out that passing vehicles generated the minimum equivalent sound pressure level of 51.3 dB. The maximum level obtained was 86.1 dB. Taking into account the range of sound level in the locations, it was decided that the selected samples would be divided into five values, so that their equivalent levels could correspond to one of the five values, *i.e.*: 56, 62, 68, 74, 80 dB. Based on this assumption, all the samples could be distributed to five classes differing from each other by 6 dB. This was to ensure that the auditory sensations coming from individual samples may be clearly differentiated.

4. Comparative analysis of results

The aim of the statistical analysis was to compare the values of features obtained with the Pulse Reflex meter with those from the LabView. For this analysis 10 calibrated 10 s signal samples (five samples from (A) location and five samples from (B) location) in classes $L_{Aeq} = 56-80$ dB(A) were chosen. The details of the calibration process are contained in Subsection 3.3. The SQ features derived from the Pulse Reflex system, version 21.0.0.567, were calculated as follows [31, 32]:

– time-varying loudness (50 ms) – according to DIN 45631 [25] and Zwicker (1989) [24];
– sharpness (50 ms) – with methods [24, 32], according to Zwicker; Bismarck [33];
– roughness (250 ms) – according to Zwicker *et al.* [34];
– fluctuation strength (1 s) – according to Zwicker *et al.* [34].

The SQ features obtained from the LabView system were determined according to the applied calculation algorithms, *i.e.* [31]:

– loudness varying in time – (2 ms) – according to DIN 45631 [25];
– sharpness (40 ms) – according to [31];
– roughness (500 ms) – according to the Aures' method [31];
– *fluctuation strength* (FS) (500 ms) – according to the time history of sound signal pressure. Fluctuation strength uses the Aures' method except that it focuses specifically on signal variations with very low modulation frequencies. The algorithm examines modulations between 0 and 30 Hz, with a special emphasis on those near 4 Hz.

For both systems the analysis in the frequency domain was performed in the range of 1–24 Bark with a resolution of half of Bark.

In order to perform a comparative analysis of SQ features, the power spectral density estimate (periodogram) was used, due to the different time window lengths in the Pulse Reflex and Labview systems. The length of the SQ feature time window from Labview was adjusted to the length of the time window in the Pulse Reflex program to assure time synchronization. The Hamming window was used.

4.1. Direct comparative analysis in time domain

10 samples of cumulative values of sound quality in the frequency bands corresponding to the classes of location (A) and location (B) of Pulse Reflex and LabView tools were then statistically

analysed (see Table 2). For comparative purposes, the results of sound quality measurements in the selected measurement points were summarized. For the purpose of examining the statistical significance of the distribution of sound quality features of two samples within LabView and Pulse Reflex, the univariate analysis of variance was performed. The adopted level of significance was $\alpha = 0.05$.

Table 2. Results of statistical analysis of parameters derived from the measurements and sound quality features.

TYPE OF ANALYSIS	L_{Aeq}	LOUDNESS	SHARPNESS	ROUGHNESS	FLUCTUATION STRENGHT
Correlation coefficient	56	0.8034	0.9808	0.6396	0.1350
	62	0.6379	0.9700	0.6552	0.3463
	68	0.9390	0.9784	0.7829	−0.3853
	74	0.5964	0.9808	0.9587	0.2847
	80	0.7647	0.9437	0.7928	−0.8670
Standard deviation	56	0.1465	0.1357	0.9620	0.1377
	62	0.4013	0.1627	0.9604	0.3073
	68	0.9509	0.2275	1.0204	0.3601
	74	1.3355	0.2874	0.9993	0.4110
	80	1.6178	0.4115	0.8759	0.4013

The results presented in Table 2 are related to the statistical analysis of SQ features for the tested samples in locations (A) and (B). The presented results were referred to the assigned ranges of L_{Aeq} classes.

The tested 10 s samples represent acoustic events of passing vehicles, *i.e.* individual passenger cars. All samples were calibrated with reference to the L_{Aeq} classes. According to the assumptions of the research, the samples prepared in this way will be used in the next stage of research, *i.e.* in the psychoacoustic studies.

Figure 1 shows time characteristics of changes in time-varying loudness, designated for the audio samples recorded in a particular location, using the considered systems. There is clearly a high compatibility visible in the obtained characteristics, regardless of the location of the measurement. In both cases, the values obtained with LabView are slightly higher than the values obtained with Pulse Reflex. For location (B), there were higher instantaneous values of time-varying loudness compared with those for location (A). The obtained results may indicate that the perceived time-varying loudness for sample B is higher than the time-varying loudness for

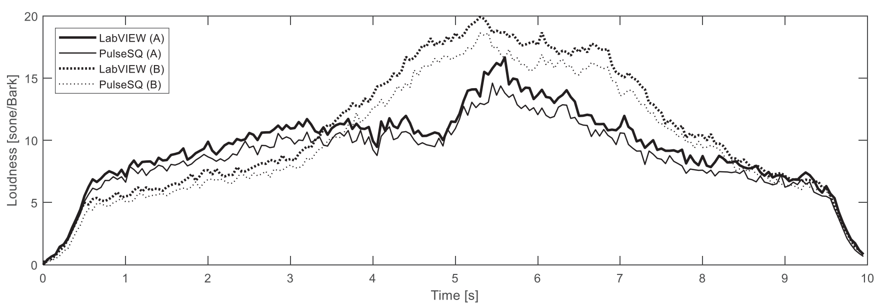

Fig. 1. Time-varying loudness.

sample A. This result is different from the results of noise measurements expressed by indicators L_{Aeq}, L_{Amax}, L_{Cpk}. The reason for this is related to the shape of the corrective curve A, used to determine noise indicators (high dumping in the low and high frequencies). The process of determining the time-varying loudness parameter substantially differentiates from the method for determining the noise indicators.

4.2. Direct comparative analysis in frequency domain

The SQ result samples obtained for the locations (A) and (B) were statistically evaluated to check whether the differences in the obtained characteristics are statistically significant. The first step of the analysis consisted in checking whether the variables have a normal distribution. If yes, then either the T-student test (variances known) or the Mann–Withney U test (variances not known, but should be equal) was performed. Otherwise, the Welch's t-test was employed.

Interpretation of the obtained results showed that for loudness, sharpness, roughness and fluctuation strength, the differences in the individual samples are statistically significant (Figs. 2 and 3, Table 3). On the other hand, for the loudness measure, there is a lack of statistical significance of results between LabView and Pulse Reflex (Fig. 2, Table 3).

Table 3. Results of statistical evaluation features of SQ samples (A) and (B) examined with LabView and Pulse Reflex tools (YES – no basis for rejection, NO – reject the hypothesis).

LOCATION	MEASURE OF SOUND QUALITY	p	RESULTS OF THE TEST FOR THE NULL HYPOTESIS	
A	Loudness	$p = 0.420$	t-student	YES
	Roughness	$p < 0.0001$	Mann–Whitney U test	YES
	Sharpness	$p < 0.0001$	Mann–Whitney U test	NO
	Fluctuation strength	$p < 0.0001$	Mann–Whitney U test	NO
B	Loudness	$p = 0.303$	Mann–Whitney U test	YES
	Roughness	$p < 0.0001$	Welch's t-test	NO
	Sharpness	$p < 0.0001$	Mann–Whitney U test	NO
	Fluctuation strength	$p < 0.0001$	Mann–Whitney U test	NO

It should be noticed, that the absolute values of individual parameters, determined by using the considered systems, differ greatly among themselves. This is confirmed by the results of statistical analysis, on the basis of which, compatibility of the measurement systems was found only for the loudness parameter. Taking into account the relative changes observed for each location, an additional SQ compatibility analysis was performed. For this purpose, the values obtained with a particular system were divided by each other for considered locations.

Figures 2 and 3 show the distributions of sound quality indicators: loudness, roughness, sharpness, and fluctuation strength expressed in the Bark scale. The shapes of the roughness parameter obtained by the two considered systems differ much.

In Fig. 3 (right) for the Pulse Reflex system, parameter variation above 16 Bark was observed. For lower frequencies, the characteristics for locations (A) and (B) are constant. For the results obtained using LabView, the characteristics for locations (A) and (B) are alternately interleaved. However, starting at 16 Bark, the fluctuation strength for location B exceeds the fluctuation strength for location (A) regardless of the measurement system used.

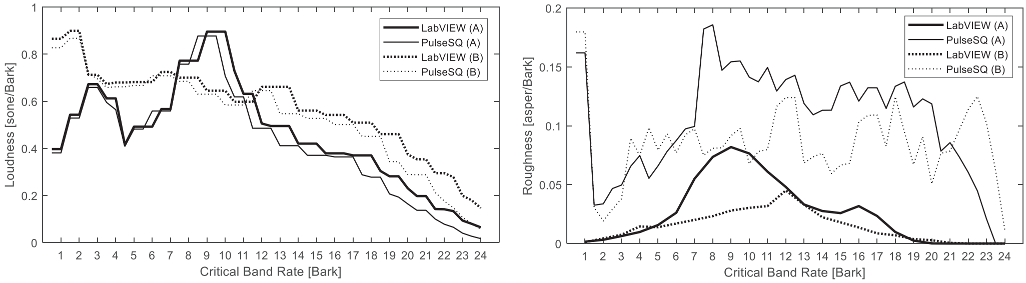

Fig. 2. Loudness in the frequency bands (left), roughness in the frequency bands (right).

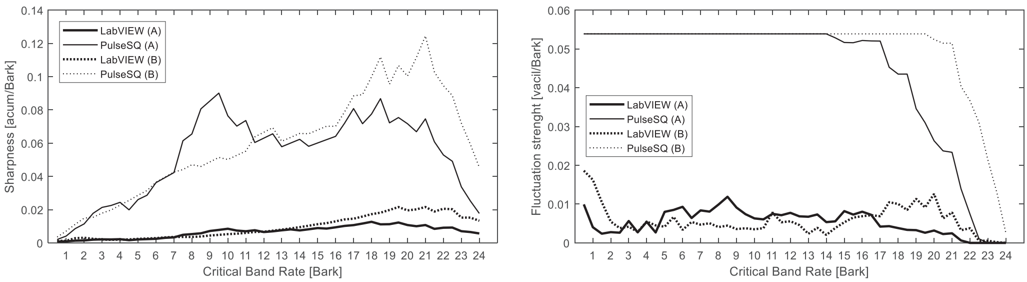

Fig. 3. Sharpness in the frequency bands (left), fluctuation strength in the frequency bands (right).

4.3. Relative comparative analysis for frequency domain

A relative comparative statistical evaluation of SQ result samples obtained for locations (A) and (B) was performed to check whether the differences in obtained characteristics are statistically significant or not. The same samples as described in Subsection 4.2 were used in this scenario.

However, by analysing the shape of the characteristics obtained for a given system in the considered locations, there can be observed relative compatibility. For both Pulse Reflex and LabView, the roughness values are higher for the sample (A) compared with the values obtained for the sample (B). This is especially true for the ranges of 6–12 and 14–18 Barks. This result can be associated with the specificity of the generated signal, which is dependent on the type of the road surface on which the vehicles were moving.

This observation is even more visible in the case of the sharpness parameter. The sharpness values are higher in the range of 6–12 Barks for location (A), contrarily to higher frequencies in the Bark scale (14–24) where the sharpness values are larger for location (B). This is generally consistent with the sound tone for each location. In the case of the measurement point (A), we are dealing with an uneven surface, which results in an increased sharpness parameter value in the range of 6–12 Bark bands. In location (B) the surface is smooth, which results in higher values of sharpness for Bark bands above 16.

In addition to the above described evaluation, the relative changes of a given parameter depending on the location were determined. The obtained results indicate that the Pulse Reflex and LabView systems, in a similar way, determine the relative change in the loudness and sharpness parameters in the whole frequency range expressed in Barks. To that end, correlation coefficients of the sample values (P(A)/L(A)) and (P(B)/L(B)) were calculated for every SQ parameter (see plots presented in Figs. 4 and 5). The difference is smallest for loudness and sharpness (the correlation coefficient exceeds 0.9) and partly for roughness (the correlation coefficient exceeds 0.68). For fluctuation strength we did not observe correlation at all (the correlation coefficient equal to −0.02).

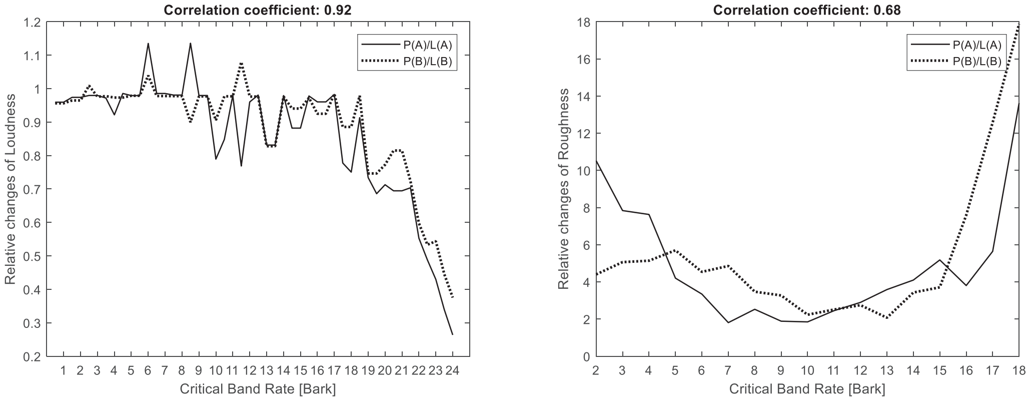

Fig. 4. Relative loudness (left) and relative roughness (right) in the frequency bands. Correlation coefficients are also presented.

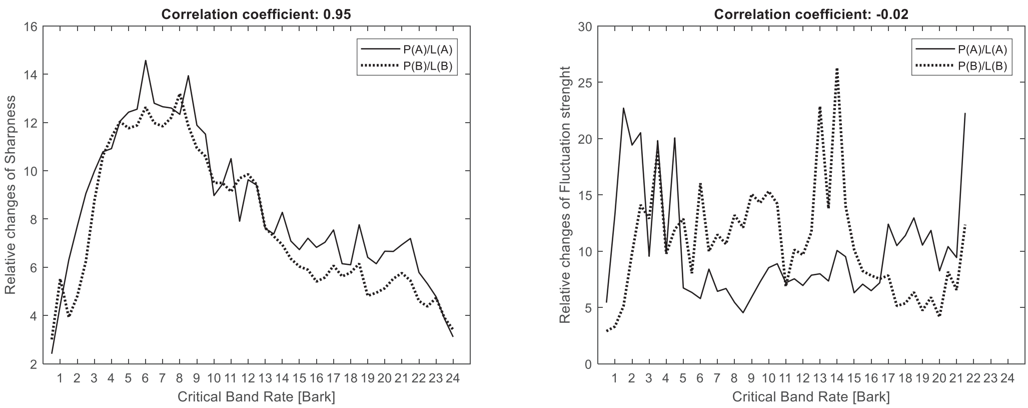

Fig. 5. Relative sharpness (left) and relative fluctuation strength (right) in the frequency bands. Correlation coefficients are also presented.

5. Conclusions

The obtained values of SQ measurement refer to two locations and two systems, where audio signals were measured and recorded. Variability of acoustic parameter values derived from the noise signals was due to the varying signal resulting from the changes in the traffic type/parameters and characteristics corresponding to the measurement locations.

The results obtained in the study indicate that there occurs a significantly strong correlation between loudness and Leq. However, the correlation analysis carried out does not take into account statistical loudness models, *i.e.* N5, N10 – as Zwicker suggests [16]. In further psychoacoustic studies, the authors will use the spectral centroid for the SQ metrics correlation. The information about the fundamental frequency of the SQ metrics distribution will be used to build the noise annoyance model.

The SQ values derived from the recorded signals using the LabView and Pulse Reflex tools show a varying degree of similarity and inconformity. The differences of results for samples (A) and (B) can likely be caused by the algorithms applied to calculate SQ parameters in LabView and Pulse Reflex. The SQ-based measurements using Pulse Reflex were performed according to the DIN 45631/A1 standard [25]. In particular, the calculation of time-varying loudness by the LabView tool was based on DIN 45631/A1 standard [25]. The results obtained from the analysed samples for this parameter (Figs. 2 and 4) do not present significant differences, which was confirmed by the statistical assessment (Table 3). It should be noticed, that in the case of calculating sharpness and roughness features with the use of the LabView tool, the Aures method was applied. In that case, the differences between the tools used in the study for the above mentioned parameters are statistically significant. Specifically, the fluctuation strength parameter seems to be problematic while assessing it is based on the traffic noise. This may probably be due to the fact that the low frequency modulation of noise is more suitable for slow varying stationary noises.

The obtained results of the distribution of parameters describing sound quality, expressed on the Bark scale may be useful in assessing the type of the road surface, especially if the surfaces differ in texture. Changes of sound tone are particularly evident in the distribution of roughness and sharpness values.

In the future the annoyance of traffic noise using the method of loudness scaling will be investigated in laboratory conditions. The measurements will be performed to constitute a reference for replicating acoustic conditions occurred in an immediate vicinity of the road in the subjective listening tests. Moreover, additional analyses will be performed in accordance with a newly issued ISO standard [28].

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